

Science-Based Stockpile Stewardship

An overview

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Los Alamos was founded as the world's first nuclear weapons laboratory. Brilliant scientists from different nations, all committed to defending freedom, dedicated their time and offered their best understanding of physics, chemistry, engineering, and materials science to design and manufacture the first nuclear bombs. They had no previous experience, only the minutest amounts of the nuclear material for most of the project, and at the end, only material for one test. The scientists' only option was to exploit the full power of the scientific method, whereby concepts are challenged and the iterative cycle of theory, experiment, evaluation, and innovation leads to confidence in prediction.

When the Laboratory opened, the basic concepts for a gun-assembled weapon and an implosion weapon had already been formulated at the 1942 University of California, Berkeley, summer study, but the detailed physics necessary to assemble several critical masses fast enough to produce a successful nuclear explosion had to be acquired and demonstrated. The fundamental properties of the neutron chain reaction—the number of neutrons released per fission, the energy spectrum of fission neutrons, and the cross sections for neutron-induced fission, neutron capture, and neutron scattering—were measured at a feverish pace. Basic material and chemical properties of uranium-235 and plutonium-239 were determined. Diagnostics, such as flash radiography, were devel-

oped to measure the progress of an explosively driven implosion, and numerical methods were developed to calculate the implosion. Analytical methods, combined with judicious approximations, were used to estimate the amount of nuclear material that would be needed and to predict the efficiency of the nuclear explosion. As the experimental numbers became available, they were used to determine the parameters in the theoretical models. The resulting predictions for the explosive power released could be trusted within some margin of error.

The yield predicted for the Trinity test at Alamogordo, New Mexico, was the equivalent of 5 to 13 kilotons of the explosive TNT. The measured yield was even higher—17 kilotons. Considering that the designers were treading on unexplored terrain, these results were an awesome testament to the power of scientific prediction.

Sixty years later, our core mission bears some remarkable similarities to the mission of the early days. Today, the vast nuclear weapons complex of the Cold War, built after Trinity, has been reduced in size. Los Alamos and our sister laboratories, Sandia and Lawrence Livermore National Laboratories, are now responsible for all the science, much of the engineering, and a significant portion of the manufacturing needed to maintain the enduring stockpile. As a steward of the weapons in our stockpile, Los Alamos was challenged by the president to cer-

tify their safety, security, and performance—and to do so in the absence of yield-producing nuclear tests. The nuclear weapons program at Los Alamos relies on the scientific method to acquire the needed knowledge and to formulate predictions based on that knowledge. Stewardship means that we must predict performance as weapons age, identify the parts that need refurbishment, certify performance when weapons contain parts that are made from new materials and that have been manufactured by new techniques, and prepare for possible redesign of present systems to meet the changing needs of an increasingly complex world. However, we must accomplish these tasks through predictive capabilities, without resorting to actual nuclear weapons testing. This approach has never been attempted in the history of engineered devices. Achieving and demonstrating the required level of predictability demand at least as much (if not more) ingenuity and skill today and in the future as they did 60 years ago.

Los Alamos has been a science laboratory throughout its history. It has built and maintained the nuclear deterrent through its broad investment in science and technology and in the talented people who continued to create ideas that change the world. This overview and the articles that follow it show how our continuing investment in frontier science, first-rate scientists, and the rigor of the scientific method are producing sustainable nuclear stewardship in the twenty-first century.

Development of the Enduring Stockpile

Only by reviewing the methodology used to create the existing nuclear weapons stockpile, can we convey the scientific challenges of modern stewardship. During the Cold War, changing military requirements drove the design of new weapons systems. Increasingly,

lighter, smaller, more accurate, and specialized warheads were required to maintain deterrence against the growing sophistication and hardness of the threat. These new weapons were designed to perform reliably during much more rigorous and demanding operating conditions, referred to as stockpile-to-target sequences, and ultimately deliver on target the certified yields, known as military characteristics. Later, requirements for increased safety and security led to the development of insensitive high explosives, fire-resistant weapons components, and other surety features. Weapons were manufactured in large quantities to counter the Soviet buildup. However, for logistic and maintenance simplicity, as well as to ensure a credible deterrence posture, the military required many identical copies of a few, well-honed, and fully characterized designs. That is, all these designs had their pedigrees in nuclear tests and in nonnuclear integral tests (weapons tests in which surrogates replaced the fissile materials). These tests improved our basic understanding of weapons physics and permitted us to develop an expanding body of empirical experience. This experience provided us with a means to improve and fine-tune weapons performance.

At the same time, weapons designers developed a series of computer codes, now designated as “legacy codes,” for weapons design. These were design aids to refine the qualitative understanding of the physical processes involved. Although not capable of directly predicting the results of nuclear tests to the accuracy required for the military, the codes were calibrated empirically to fit test results. Hence, the codes were a valuable, very sophisticated interpolation, and even extrapolation, device for designs in the neighborhood of those tested. The adjustments to the codes made directly from test experience gave designers a “feel” for how their incomplete simula-

tion tools related to materials behavior under the physical conditions achievable only in a nuclear test. The expert judgment gained from full-scale tests remained a key component in the designers’ craft during the Cold War era.

Stockpile Maintenance without Nuclear Testing

Los Alamos designers were very successful at meeting the safety, performance, and reliability criteria of the military: They designed five of the seven weapons systems currently in the enduring stockpile. However, the focus of their activity changed abruptly toward the end of the Cold War. First, the nuclear weapons stockpiles that had accumulated in both our country and the Soviet Union far exceeded the size necessary to maintain stability. Building down the stockpile became more important than building it up. Second, there was a growing national commitment to global nonproliferation goals and to preventing terrorists from acquiring nuclear materials and weapons. Finally, by fiat, the United States and other declared nuclear states announced a moratorium on underground nuclear tests. Our last nuclear test occurred in 1992, just after the end of the Cold War.

In 1992, our nation adopted testing constraints laid down by the Comprehensive Test Ban Treaty. That is, we agreed not to perform a weapons test involving an uncontrolled nuclear chain reaction. The complete ban on nuclear tests, at “zero yield,” was seen by some policymakers as a mechanism to slow the proliferation of nuclear weapons to nonnuclear states. Without the option to test, it was argued, treaty members would be denied the key means of assessing and demonstrating nuclear capability.

For the weapons designers at Los Alamos and Lawrence Livermore, the two weapons design laboratories, the

change to a nontesting environment was intellectually as “seismic” as the nuclear tests had been in actual fact. Testing had been the ultimate guarantor of reliability and performance. Testing was the key means not only for certifying new systems and developing expert judgment but also for verifying the continued safety, security, and performance reliability of the weapons systems for which the designers were still responsible. What could possibly replace the sensation of having the ground heave underfoot after an actual nuclear test?

The answer to that question, arrived at jointly by the Department of Energy and the design laboratories, was a formal program in science-based stockpile stewardship. The idea was to build a strong base of scientific understanding, combine that base with our historical test experience, and from that combination, develop the tools to predict the performance of stockpile weapons without resorting to new nuclear tests. From small-scale physics experiments combined with theoretical analysis, scientists would develop a deeper understanding of detonations, hydrodynamic behavior, and materials behavior and hence be able to develop more-accurate weapons physics models. The new models would be incorporated into a new generation of simulation codes developed under the Advanced Simulation and Computing (ASCI). New facilities would be built to do more accurate nonnuclear integral tests of whole weapons systems. The integral tests would provide a method to validate the computer simulations of the early stages of weapons performance. Archival data from past nuclear tests would be used to validate the codes during later stages of weapons performance. Finally, through vastly expanded computers for carrying out more realistic simulations of weapons performance in three dimensions, weapons scientists

would be able to predict performance of the stockpile weapons with acceptable levels of confidence, maintaining the stockpile with no additional tests.

The need for scientific prediction, handicapped not by a lack of nuclear material but by the injunction against nuclear testing, has required a major cultural change for the weapons program. However, as new simulation capability has come online, as new theories and models have been developed and incorporated into the weapons design codes, and as new experimental tools confirm our predictions, optimism has grown among designers that science-based stockpile stewardship could be sustained for “near”-stockpile configurations.

Successes of Stewardship

Enhancing Predictive Capability. A brief sampling of successes over the last decade illustrates the new understanding and scientific tools that are leading to enhanced predictive capability. Many of these successes are discussed in the articles included in this section on nuclear stewardship. Most remarkable are the increases in simulation capability achieved through ASCI. Both the level of detail in the simulations and the speed and size of the computing platforms have increased by many orders of magnitude. A major milestone for the ASCI multiphysics codes was the first end-to-end three-dimensional simulation of a nuclear weapon explosion—from high-explosive detonation to nuclear yield. This capability provides a strong foundation on which to build predictive simulation.

Although such calculations take several months even on the new machines, they were simply unimaginable just a decade ago. One of the challenges now is to achieve the shorter turnaround times needed for code validation and production use.

To be predictive, our simulations

must incorporate theories and models derived from and validated through a strong experimental science program. Our experimental program covers all the scientific areas related to weapons performance. It also spans the range from small-scale basic physics experiments to so-called integral experiments, which test the behavior of a whole weapon system just short of a nuclear test. In our gas-gun experiments, for example, we shoot a projectile at a small flat plate of plutonium to measure the material ejected from the surface. Those experiments provide basic physics information on dynamic response to shocks. On the other hand, in an integral experiment, we might replace plutonium with a surrogate, say, a heavy metal, in a geometry that closely represents that in a weapon system. Integral experiments known as subcriticals are conducted underground at the Nevada Test Site. In these experiments, high explosives drive the implosion of an assembly in a weaponlike geometry using amounts of plutonium that do not give nuclear yield. Thus, the simple experiments build the basic physics knowledge that is incorporated into the simulation codes, and the integral tests help us validate the predictions of systems performance.

The iterative process of experiment, theory, and simulation has already yielded significant improvements in some of our physics models, including a model for the propagation of detonation waves around corners and the development of more accurate equations of state for plutonium. The materials models have a direct impact on certification. Our new ability to accurately model the detonation of insensitive high explosives in complex geometries has helped us address a major stockpile issue. That new model has also helped us analyze accident scenarios and support the authorization basis at the Pantex manufacturing facility. The work on the equation of state of plutonium is contributing to

the certification of the newly manufactured pit for the W88 warhead. The pit will be certified through a large number of subcritical tests in which the weapon assembly contains a partial plutonium pit.

Simulation tools are also being developed to model manufacturing processes such as plutonium casting and to model materials behavior under weapons conditions. These computer simulation tools allow exploring a whole range of these processes for a fraction of the time and expense involved with real materials and equipment.

Another major success is the development of DARHT, the world-class dual-axis x-ray machine for obtaining high-quality, high-resolution images of hydrotests, which are nonnuclear integral tests of hydrodynamic implosion. Experiments at the DARHT facility are being used to address system performance and to validate weapon system codes. Very recently, radiography of a hydrotest at DARHT enabled us to resolve a major uncertainty in the calculation of implosion and thereby address an important stockpile certification issue.

The invention and application of proton radiography, a powerful new imaging capability, is one example of the enormous creativity of our scientific staff. This new technique is now being implemented at the rate of about 40 experiments per year at a proton “microscope” system installed at the Los Alamos Neutron Science Center (LANSCE). Short proton pulses passing through an electromagnetic lens system produce rapid multiple-time images of dynamic events with a resolution that can be as good as 15 micrometers. The movielike sequences lend insight into basic material behavior under extreme pressures and speeds and under dynamic conditions that would otherwise be difficult to access diagnostically. Protons have the advantage of discriminating among materials of different atomic

numbers, thus enabling the capability to “identify” materials in mixed conditions. (X-rays are not sensitive to atomic number.)

The two intense neutron sources at LANSCE also continue to yield important new nuclear data for weapons design and new characterization of plutonium and other weapons materials. Recent measurements at the Weapons Neutron Research facility at LANSCE, combined with theory, led to a major (30 percent) change in the cross section for the important (n,2n) reaction, in which the isotope plutonium-239 becomes plutonium-238. As a result, relative changes in plutonium isotope abundances became a reliable metric for determining the fission yield of plutonium in past nuclear tests. That development, in turn, resulted in an important reanalysis of the nuclear tests that underpin certification of the current stockpile. At LANSCE’s Lujan Center, inelastic neutron-scattering measurements have produced the first-ever determination of the phonon density of states of plutonium, an important component of our understanding of the equation of state of plutonium. Also at the Lujan Center, a major new detector system will enable us to measure the nuclear properties of very small radioactive samples, some weighing as little as one milligram. That capability will allow us to reanalyze radiochemical information from past underground nuclear tests with confidence that the physical processes determined from the data are correct and predictive.

Stockpile Maintenance, Manufacture, and Manufacturability. Science-based stockpile stewardship involves more than developing the tools to predict performance. As a steward of the stockpile, Los Alamos is also responsible for maintaining the existing stockpile through a program of surveillance and response—taking weapons out of the stockpile, examining them, and solving any observed problems. One

type of response is the life extension program. In the next decade, this program will call for replacements or modifications of specific components in the stockpile, and thus it presents major engineering and resource challenges.

Los Alamos has also taken on some production responsibilities as facilities were shut down across the national weapons complex. Our most visible new task is to manufacture the plutonium pit, the heart of the weapon primary, but we are also responsible for manufacturing detonators, neutron generators, beryllium components, and other parts.

In pit manufacture, we have had to recreate the entire technology of the Colorado Rocky Flats Plant in a changed environment, where many materials and processes used at Rocky Flats are neither available nor permitted. Developing and qualifying the new processes and certifying the performance of the product without full-scale testing have been the first big test of the stewardship regime. We have changed not only our technology but also our traditional ways of doing business. Fortunately, our dedicated staff at the plutonium facility responded with their full measure of skill and intensity. By the start of the calendar year, they had produced a number of system qualification test pits and just recently delivered a completely weapons-qualified (“certifiable”) pit—a major achievement. In a parallel effort, our program leaders have initiated the development of sophisticated process monitoring and control procedures that guarantee quality during the manufacturing process. This investment in yet another aspect of predictive capability should enable us to sustain the pit manufacturing capability in the present environment of changing requirements and small throughput. Both the life extension program and our different production tasks clearly call for a science-based methodology to establish priorities and quantify our

level of confidence in the new or changed components. Responding to an aging component with a plan to replace all identical components in the stockpile and thus “rejuvenate” the stockpile may be a very expensive decision. Without careful assessment of performance versus impact, one can make poor decisions. As described in the next section, we are currently developing a quantitative framework for guiding such decisions and building confidence in stewardship.

A Certification Methodology

Each year, the director of the Laboratory must assess the weapons in the stockpile for safety, performance, and reliability. This assessment must consider whether military characteristics and requirements can be met without a return to nuclear testing. In the current stewardship regime, the key question we face in the annual certification is, “What is the relationship between key weapon-performance metrics and the design margins of the system?” Furthermore, how far can we stray from the ideal design environment (materials, age, and tolerances) before a weapon will fail to meet its military requirements? And how can we quantify our confidence? That is, how much do we trust our predictions?

These are tough questions that have never before been addressed or quantified. Consequently, the policy community has challenged us to provide a rigorous scientific approach to reach closure on scientific issues and to quantify the level of confidence with which we certify the stockpile. In response, both Los Alamos and Lawrence Livermore have developed a certification methodology that revolves around quantifying margins and uncertainties for the various stages of weapons performance. By judging our progress on the problem of decreasing the uncertainties, we

have the means to rank scientific and technical investment. For example, we will be able to decide whether a particular process must be modeled at the molecular or macroscopic level to reduce uncertainty or whether some modest parametric representation would be adequate—all based on assessing the impact of the uncertainty on our confidence in performance. We know that complete predictive capability of weapons performance is not possible, but we will be able to estimate our degree of confidence and specify the requirements for increasing that confidence based on quantitative performance-related measures.

This new methodology has an important corollary. It can help translate the unwritten lore of our best designers into solid guideposts for the emerging generation of new designers. Our best designers, like innovators from every field, did not always write everything down, nor was there ever a prescribed method to document the detailed interplay between simulation and testing. The experienced designers had learned how to compensate for less-than-predictive models by adjusting empirical parameters to ensure enough “predictive ability” in yield and diagnostic measurements and to anticipate the “next” underground test. Now, a new methodology focusing on margins and uncertainties allows for more explicit representation and quantification of essential design decisions and judgment.

Most important in the long term is that certification without testing be sustainable. Sustainable means not only that we continue to increase our science and engineering understanding of the weapon system but that we use that knowledge to make cost-effective decisions about the scope of weapons refurbishment and to better address the issues observed in the aging stockpile.

The Current Global

Environment

Today, the international and national security environments have changed radically and have, to some extent, become entwined. Nations that were once our formidable and determined nuclear enemies have now become our real or emergent allies. Although the Cold War, a struggle that seemed destined to permanence, has ended, the threats to world peace remain real, and arguably, the instability around the globe is greater. Among the new and emergent allies, there is a new determination to stop the growth of this incipient instability—one brought to us by the harbingers of terror.

Against such a backdrop, our nation has been reevaluating its nuclear posture. Of course, nuclear capability remains the ultimate deterrent, but ever more voices raise questions about the nature and effectiveness of that deterrent. Here, effectiveness is not discussed in destructive terms, but it refers to maintaining real deterrence against radically different enemies and targets. It may be argued, and it would certainly be ironic, that the existence of nuclear weapons with lower levels of collateral damage and therefore increased “usability” may be the greatest deterrent and thereby the greatest force against their own actual use. The aim would still be to never have to use the weapons.

Policy Changes

In early 2002, the Bush administration issued the findings from a Nuclear Posture Review that placed nuclear weapons in a new and different context. In the past, we described deterrence in terms of an offensive triad composed of intercontinental ballistic missiles, submarine-launched ballistic missiles, and strategic bombers, each carrying nuclear warheads capable of delivering kilotons, if not megatons, of

explosive power. Having evaluated the changed environment in both threat and technology, the Nuclear Posture Review offers a new triad, in which the three nuclear offensive capabilities above appear on one leg of a triangle, joined and complemented by strategic nonnuclear weapons. This change recognizes that precision delivery systems with conventional warheads, such as those exercised during the Gulf War and, more recently, in Afghanistan and Iraq, can now operationally achieve some of the strategic objectives that only nuclear weapons could have achieved in the past.

The first choice is always to avoid direct use of nuclear weapons and to use them only as a deterrent. However, in the event they were required because the destructive effect needed is achievable only through nuclear processes, our nation would not want them to have unacceptable collateral effects. For example, it would be less “effective” to threaten to use a nuclear weapon to destroy chemical and biological agents in a deeply buried and hardened arsenal if the explosion would produce widespread nuclear contamination. Consequently, there may be fewer nuclear weapons in the new triad, but they will probably have to be more robust and address new strategic problems.

The review also introduces a vital, new component to the new triad, namely, responsive infrastructure. In a world where technology is changing quickly, where emerging threats are difficult to identify in advance, the review challenges the science and technology community to develop flexible and adaptive capabilities. What does that mean for the nuclear weapons community?

Advanced Concepts

In the past, we were asked to build thousands of identical warheads to be

placed in ballistic missiles, each directed toward specified targets. Today, the technical and policy communities are increasingly seeing a need for new kinds of devices. Depending on how the threat evolves, we may be tasked to build relatively small numbers of weapons of very special and limited capability. If so tasked, we may extrapolate some of those weapons designs perhaps from the designs in the existing stockpile. Those would be moderately easy to certify without testing. A great number of possible “new” weapons might be based on design concepts and weapons systems that were tested in Nevada before 1992 but never implemented in the stockpile. Depending on the testing pedigree, these may or may not be straightforward to certify without testing.

The Nuclear Posture Review has opened the door to serious thinking about advanced concepts. The timing could not be more opportune. Our experienced designers are nearing retirement, and before they stop working, they must mentor the new designers. Study of advanced concepts offers a dynamic environment for training and transfer of expertise to a new generation. Unlike stewardship of the last decade, which focused on narrow aspects of weapons physics at times, advanced concepts require thinking through the performance of the system as a whole and thus keeping the integrated design capability alive.

The Future and the Need for Talent

I believe that stewardship is at a crossroads. In the last decade, we have achieved a great deal without testing and have been able to continue to certify the stockpile. However, we are starting to address physics and engineering issues that may not be so amenable to our present tools. For many reasons, the weapons laboratories are not yet able, unfortunately, to

develop and validate the new tools fast enough. We have several major stockpile systems to maintain (for example, through life extension), and those efforts are as significant a load as any placed on us during the Cold War.

While the national and international environments compel us to maintain, for the foreseeable future, the science, engineering, and manufacture that underpin the existing nuclear weapons capability, we must also envision how the nuclear community might contribute to a more agile and responsive defense without resorting to testing. In other words, we must create the deterrent of the future.

During the past 10 years, we have prepared for these demanding challenges by embracing a strong scientific approach and developing the tools for sustainable stewardship. Now, we need to continue recruiting and nurturing the best talent to solve the wealth of science and engineering challenges that the program faces. The fact that those problems can now be tackled with some of the most advanced simulation and experimental tools available gives us hope. The determination and continued dedication of our staff sustain that hope. ■

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